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'Blizzard of the century' — the storm of 12–14 March 1993 over the eastern United States

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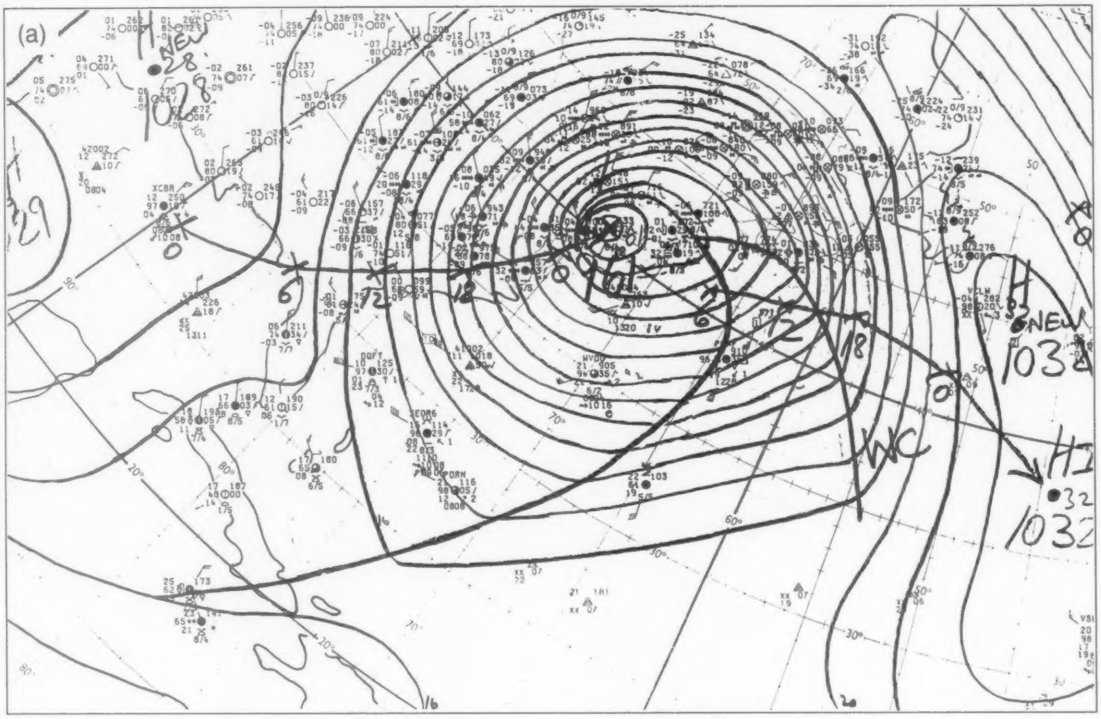
This article was commissioned of Professor Forbes as a recent example of cyclogenesis to illustrate a chapter in Images in weather forecasting, *a massive work on the interpretation of satellite and radar pictures to be published for the Meteorological Office by Cambridge University Press at the end of this year. Shortly after the paper was received, Taylor gave the Editor a demonstration of the ATD system's capabilities. Forbes has kindly allowed this to be included and the whole paper to be printed here.*

A storm described by some as the 'blizzard of the century' swept across the eastern portion of the United States on 12–14 March 1993. Fig. 1(a) is a copy of the United Kingdom Meteorological Office (UKMO) working chart at 0600 UTC on the 14th and Figs 1(b) and 1(c) are Meteosat views of the storm at 0000 UTC on the 14th and 0000 UTC on the 15th, respectively. In the latter, note the landmarks of Florida and the Great Lakes. The vigorous low-level convection just offshore can be seen to have moved from the Gulf of Mexico to the Eastern Seaboard as the storm has moved north-east. Fig. 2 shows the track and central pressure of the surface low-pressure centre. A number of stations in the south-east attained all-time low-pressure records as the storm passed.

Many locations from the mid-Atlantic states (e.g. Pennsylvania, PA) southward experienced their greatest all-time single storm snowfalls or 24-hour snowfalls, and achieved record depths of snow on the ground. Governors of several states (e.g. PA and West Virginia, WV) banned all but emergency travel. Fig. 2 shows the swath of the heaviest snowfall, exceeding 30 cm. The majority of the outlined area received 50 cm or more of new snow from the storm. Most locations within the heavy snow area experienced a period of snow falling at a rate in excess of 2 cm h^{-1}, and rates in excess of 7 cm h^{-1} were reported. Many stations within the heavy snow area also experienced a period of thunder accompanying the snow. Locations along the eastern edge and just east of the heavy snow track experienced an initial period of heavy snow, followed by or mixed with ice pellets and freezing rain. Often the ice pellets were driven by wind gusts of 40 kn or more.

At least 112 fatalities were attributed to the storm, including at least 26 deaths from tornadoes, severe thunderstorms and flooding which ripped across Florida on the evening of 12 March (FL on Fig. 2). Other causes of fatalities included traffic accidents, exposure, and heart attacks while shovelling snow. At least 15 died in Pennsylvania, three in Cuba, and four in Quebec, Canada. The storm also produced strong wind gusts in many places, and caused high tides and beach erosion.

(a)



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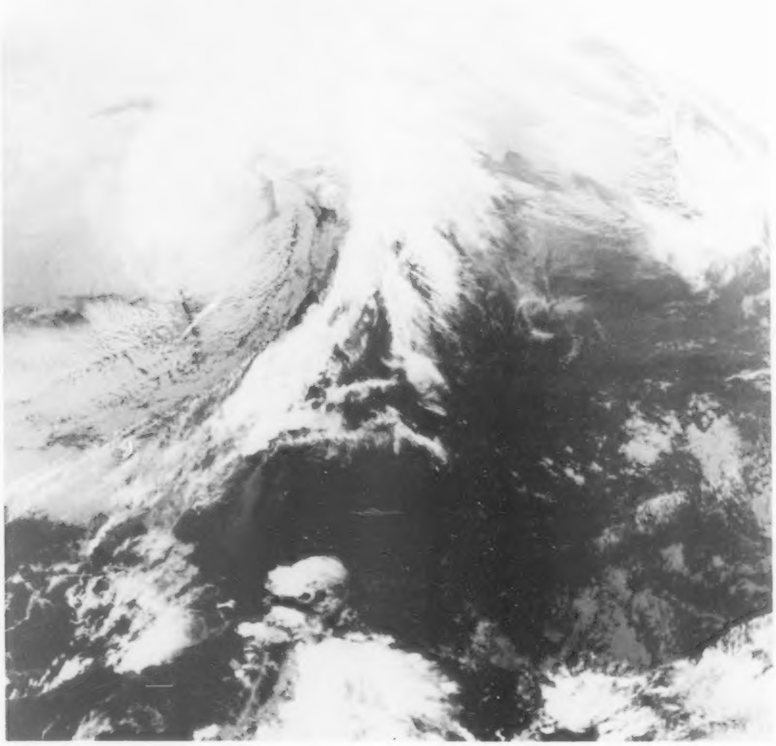

Figure 1. (a) Working chart from the Central Forecasting Office of the UKMO for 0600 UTC on 14 March 1993, (b) Meteosat image of the storm at 2355 UTC on 13 March 1993, and (c) as (b) but 24 hours later.

(c)

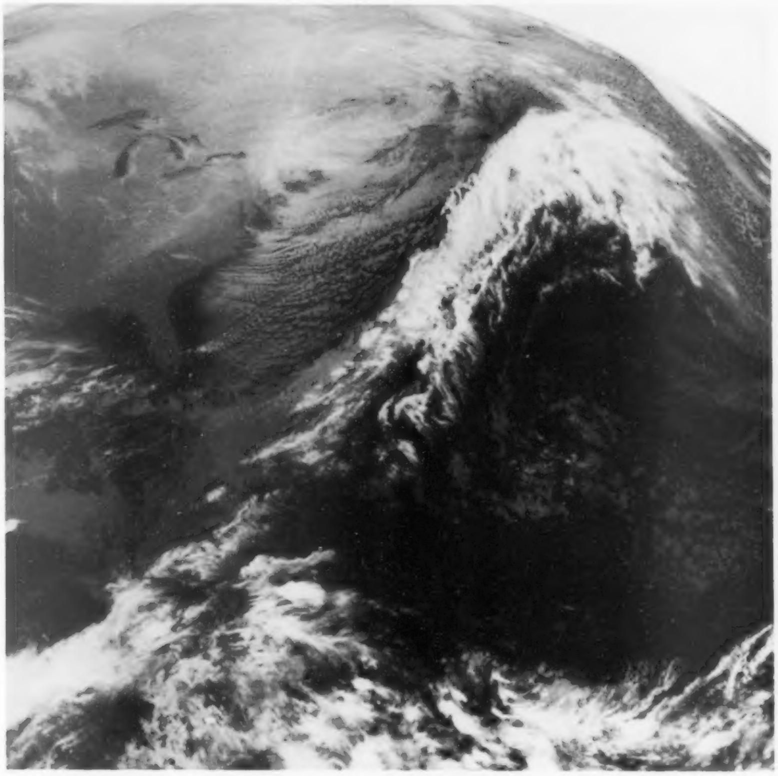

Figure 1. (Continued)

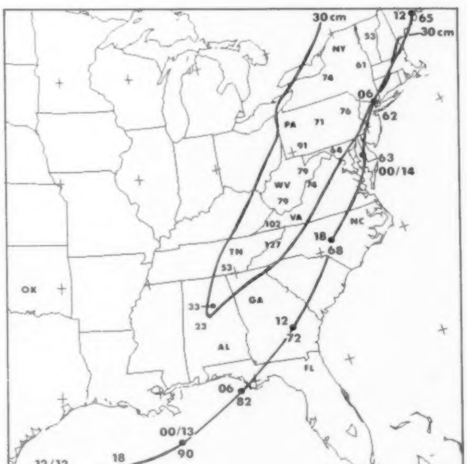

Figure 2. Track of the low-pressure centre and swath of heaviest snow accumulation in the storm of 12–14 March 1993. Storm track is depicted by heavy line with dots at 6-hour positions. Times are depicted along the track with pairs of numbers; e.g. 18/12 indicates 1800 UTC on 12 March 1993. Numbers to the right of the storm track indicate central pressure at 6-hour intervals (99 indicates 999 hPa; 82 indicates 982 hPa). Other heavy line outlines area receiving snowfall accumulations of at least 30 cm, with small numbers indicating selected points of maximum reported snowfall (cm). Letter pairs refer to States mentioned in the text (e.g. AL = Alabama).

Eighteen homes on coastal Long Island, New York reportedly toppled into the sea. Damage was reported to many shore-front homes in other states. Melting of the snow pack contributed to flooding in the mid-Atlantic States and New England about two weeks later.

The storm drew much of its energy from a strong thermal contrast, with many stations across the northern United States (and to the north in Canada) experiencing a 500 hPa temperature of −40 °C or colder on the morning of 12 March, while the Gulf Coast states had just experienced a period of near-record warmth. A massive cluster of convection developed over the northern Gulf of Mexico, and an impressive squall line developed rapidly across the Gulf. This is illustrated by the Meteosat 3 IR images in Fig. 3 and by the lightning activity detected from the other side of the Atlantic by the UKMO's ATD system. As shown in Fig. 4, the first flickers were observed off New Orleans at about 1800 UTC on the 12th and developed steadily to a peak at about 0500 UTC on the 13th and then dissipated by about 2000 UTC. (The storms over the Atlantic shown in Fig. 4(b) were discarded later as the ATD system adjusted itself to increased activity elsewhere.) The greatest activity came just as the line started to cross Florida and Cuba. The squall line produced tornadoes and wind damage across Florida; Cuba seems to have escaped tornadoes but had winds gusting to 90 kn (see 'World weather notes' in the June

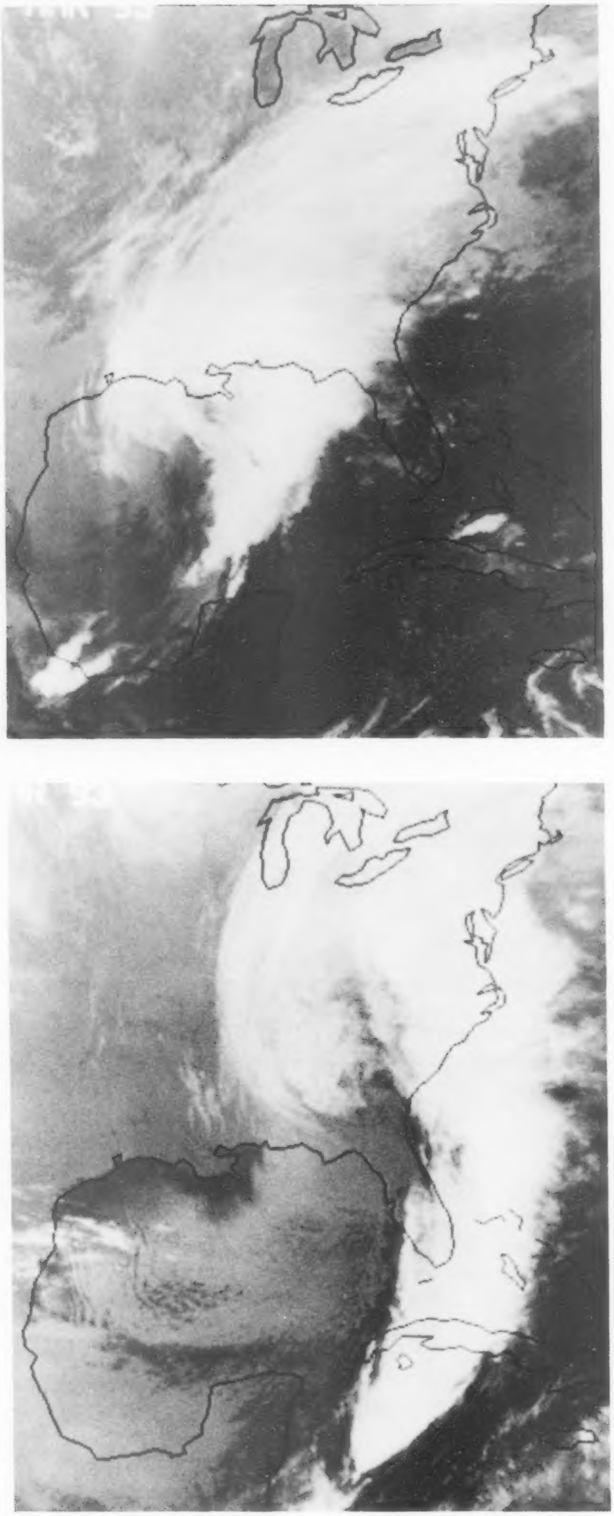

Figure 3. Meteosat 3 IR images taken on 13 March 1993 at (top) 0000 UTC and (bottom) 1200 UTC.

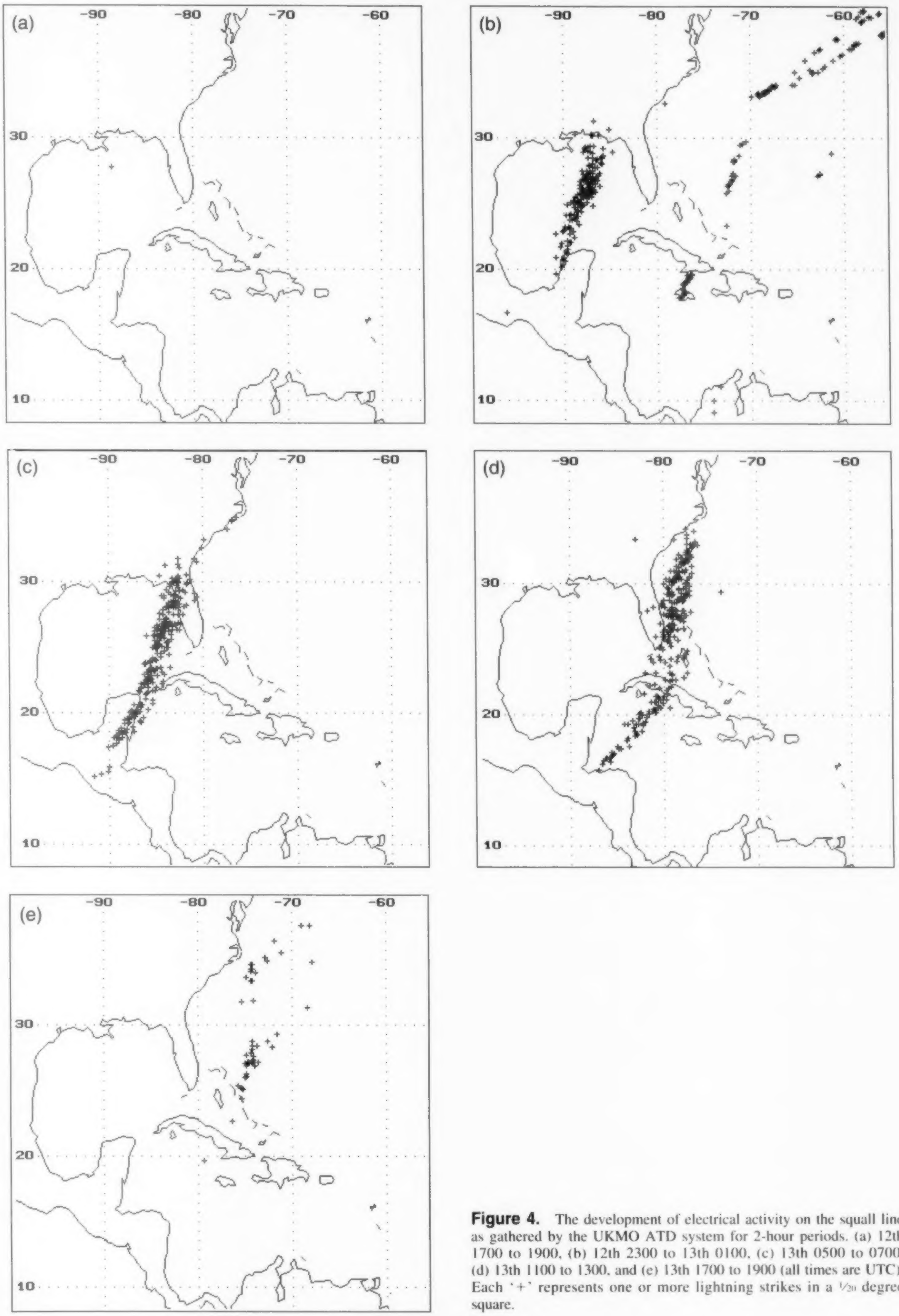

Figure 4. The development of electrical activity on the squall line as gathered by the UKMO ATD system for 2-hour periods. (a) 12th 1700 to 1900, (b) 12th 2300 to 13th 0100, (c) 13th 0500 to 0700, (d) 13th 1100 to 1300, and (e) 13th 1700 to 1900 (all times are UTC). Each '+' represents one or more lightning strikes in a 1/20 degree square.

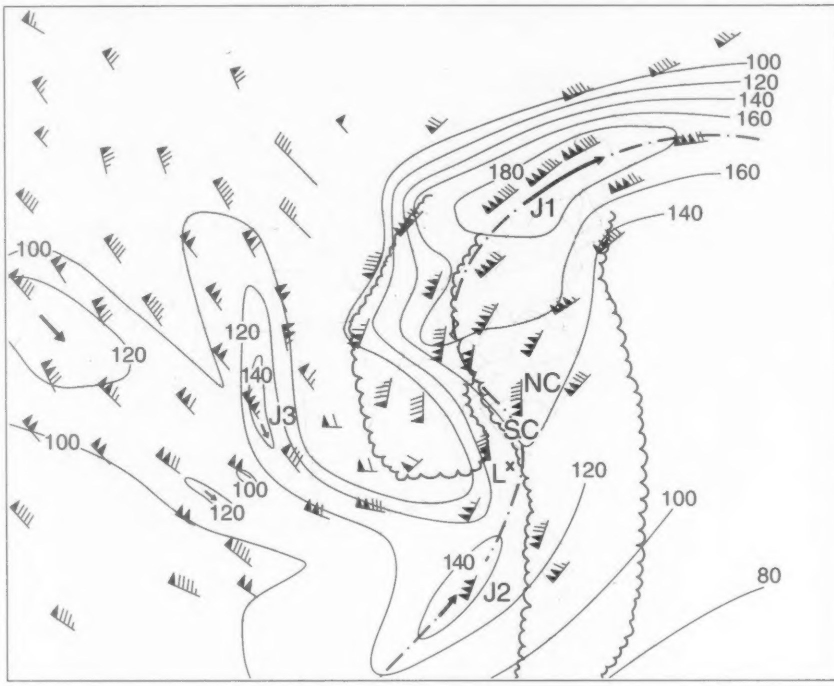

Figure 5. Maximum reported upper-tropospheric winds (kn) at 1200 UTC on 13 March 1993. The dash–dot line is the axis of maximum winds, and the scalloped line is the edge of the high cloud from Fig. 3 (bottom). J1, J2 and J3 are jet streaks, NC and SC are North Carolina and South Carolina states and L is the surface low centre.

1993 issue of *Meteorological Magazine*). The cyclone deepened from about 999 hPa to about 982 hPa while accompanying the trailing edge of the squall line across the Gulf of Mexico, making it seem likely that latent heat release within the widespread convection also contributed to cyclone intensification.

The major thermal contrast was accompanied by very strong jet stream winds, measured as high as 90 kn over northern Maine at 1200 UTC on 13 March in the upper troposphere, and exceeding 160 kn at many stations across the north-eastern United States. Winds of 200 kn were reported over north-eastern Canada at 0000 UTC on 14 March.

Fig. 5 depicts the upper-tropospheric wind pattern at 1200 UTC on 13 March. The strong winds over New England and north-eastern Canada were affiliated with the confluence of several branches of the polar jet stream, resulting in a jet streak entering Maine at 1200 UTC. Also shown in Fig. 5 is a subtropical jet streak located over the Gulf of Mexico. The cyclone intensifying over south-eastern Georgia at this time was, therefore, in the entrance region of the polar jet streak and the exit region of the subtropical jet streak. Uccellini and Kocin (1987) have shown that this type of positioning is dynamically favourable for, and common in, east coast heavy snowstorms. Divergence was present at 250 hPa throughout the region between the jet streaks, with values as large as $6 \times 10^{-5}\ s^{-1}$ near the North Carolina/South Carolina border. The branch of the jet stream and embedded streak heading south over Oklahoma were affiliated with mid-tropospheric cold advection which was helping amplify the mid and upper-tropospheric trough centred over the Mississippi River Valley.

Strong winds were observed at all levels, with gusts exceeding 86 kn reported on mountain tops in North Carolina and New Hampshire. Strong surface winds created snow drifts more than 3 m deep in places.

Fig. 6 depicts key features of the surface chart at 1200 UTC on 13 March 1993. In detailed surface analyses, the beginning of a 'bent-back' warm or occluded front or 'T-bone' front (Shapiro and Keyser 1990) can be seen to the south-west of the cyclone centre. The warm front shown along the Atlantic coast is collocated with a coastal front moving slowly inland, common in major east coast snowstorms (Kocin and Uccellini 1990). Temperatures decreased by 10 °C over about 65 km to the west of the coastal front. The storm centre tracked north-eastward along the coastal front during the day.

Perhaps the most striking aspect of this storm was the broad expanse of the east experiencing moderate or heavy snowfall rates simultaneously: 1500 km long by up to 300 km wide (Fig. 6). The snow extended well to the north of the surface low-pressure centre in a belt parallel to the coastal/warm front, and to the south-west of the cyclone centre in the region of strong low-level cyclonic

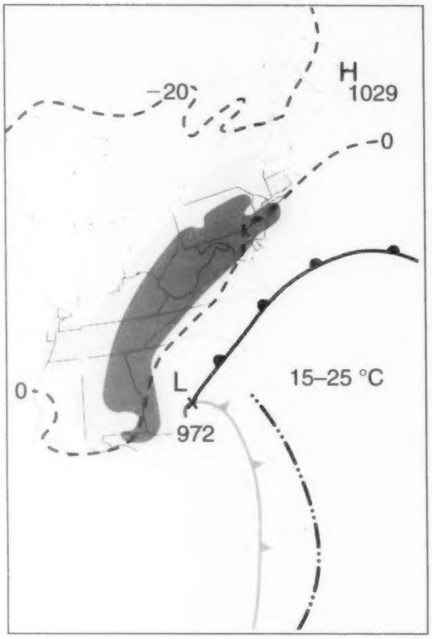

Figure 6. Surface chart for 1200 UTC on 13 March 1993. The dash–dot line is a squall line, and heavy dashed lines are are isotherms (°C). Light shading indicates falling snow and darker shading indicates moderate or heavy snowfall. Temperatures in the warm sector ranged from 15 °C near the warm front to 25 °C in the south-east of the figure.

curvature. The snow in the latter portion of the storm may have also been enhanced by upward vertical velocities in the left exit region of the approaching Oklahoma jet streak (Fig. 5). The snow ahead of the cyclone is attributed to moist south-easterly winds at low levels ascending the coastal/warm front and veering toward the north-east. This region was also experiencing positive vorticity advection (Fig. 7).

A moderate high pressure centre is located over Nova Scotia on Fig. 6. Unlike many north-east heavy snowstorms, this anticyclone had not been in residence over New England well in advance of the snowstorm, but had developed there since 1200 UTC on 12 March. Much of the anticyclogenesis is consistent with the New England region being under the influence of a strong large-scale confluence zone in the upper troposphere during the period. The development of a coastal front along the New England coast by this time (not shown) is linked to the anticyclogenesis. The coastal front forms in the confluence between onshore (easterly) gradient winds over the ocean south of the anticyclone centre and frictionally backed and orographically blocked (north-easterly) flow along the east slopes of mountains inland.

Fig. 7 shows the 500 hPa pattern at the time when the storm had just completed its period of most rapid deepening. The cyclone centre is located at the trailing (south-west) edge of a zone of strong cyclonic absolute vorticity advection that is producing rapid pressure falls over the

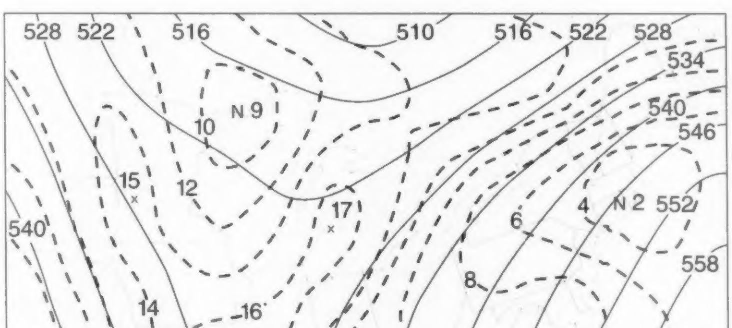

Figure 7. Heights (solid lines, in decametres) and absolute vorticity (dashed lines, in units of 10^{-5} s^{-1}) at 500 hPa, 1200 UTC on 13 March 1993. X is a vorticity maximum and N a minimum; L is the surface low centre.

region toward which the cyclone is moving. Of course, by quasi-geostrophic theory, vorticity advection must increase with height to contribute to upward motion. Fig. 8 shows the region where cyclonic vorticity advection increases with height in the layer from 850 to 400 hPa. Heavier stippling indicates larger implied upward motions. The pattern correlates fairly well to the belt of moderate to heavy precipitation. Warm advection aloft over the same region is also contributing to surface pressure falls.

Fig. 9 shows the contribution of thermal advection to vertical velocity through use of isentropic analyses on the 293 K surface. Fig. 9(a) shows the pressure levels at which 293 K potential temperature is found, and the winds relative to the isentropic surface. The surface is assumed to be moving toward the west/north-west at 9 kn, the observed velocity of the coastal/warm front. Strong upward motion is implied, as relative winds are crossing strongly toward lower pressures, overrunning the frontal surface. Thus, air from near the surface at HAT ascends the frontal zone and precipitates, reaches IAD at about 725 hPa, and then veers off to the north-east as it continues to ascend.

Fig. 9(b) shows the observed winds on the 293 K isentropic surface. The streamlines clearly show the distinction between the moist conveyor belt heading north-westward off the Atlantic Ocean and rising over the coastal/warm front, versus the polar westerlies to the west of the cyclone. This limiting streamline agrees fairly well with the western limit of the precipitation. Also shown are relative isentropic vertical velocities calculated through use of Fig. 9(a). Two corridors of strong upward motion can be seen: one just west of the surface position of the coastal/warm front, and one farther to the west near the crest of the Appalachian mountains. Upward vertical velocities as large as 21 microbars s^{-1} were computed in the corridor near the coastal front.

Fig. 10 shows soundings from along the Atlantic coast at Cape Hatteras, NC (HAT) and within the belt of moderate to heavy snow at Washington, DC Dulles International Airport (IAD). The frontal inversion can easily be seen over IAD, which separates the warm conveyor belt aloft from the cold conveyor belt beneath the inversion (Carlson 1980). The isentropic charts of Fig. 9 crossed IAD at about 725 hPa, just beneath the top of the inversion layer. Winds at this level were from the south-south-east at about 50 kn, but increased to 62 kn and veered to southerly within the base of the warm conveyor belt near 650 hPa. Thus, warm air from near the Atlantic coastline flows north-westwards, overruns the frontal surface and cools moist adiabatically. In the process, precipitation occurs first as moderate rain, then ice pellets, and finally moderate to heavy snow as the initially warm air is progressively cooled during its ascent.

Figure 8. Differential advection of absolute vorticity in the layer from 850 to 400 hPa at 1200 UTC 13 March 1993. Areas within the hatched line but without stippling represent weak contribution to upward motion from differential vorticity advection. Light and heavy stippled areas represent moderate and strong upward motion contributions. Areas labelled with D have a decrease of vorticity advection with height, contributing to downward motion.

(a)

(b)

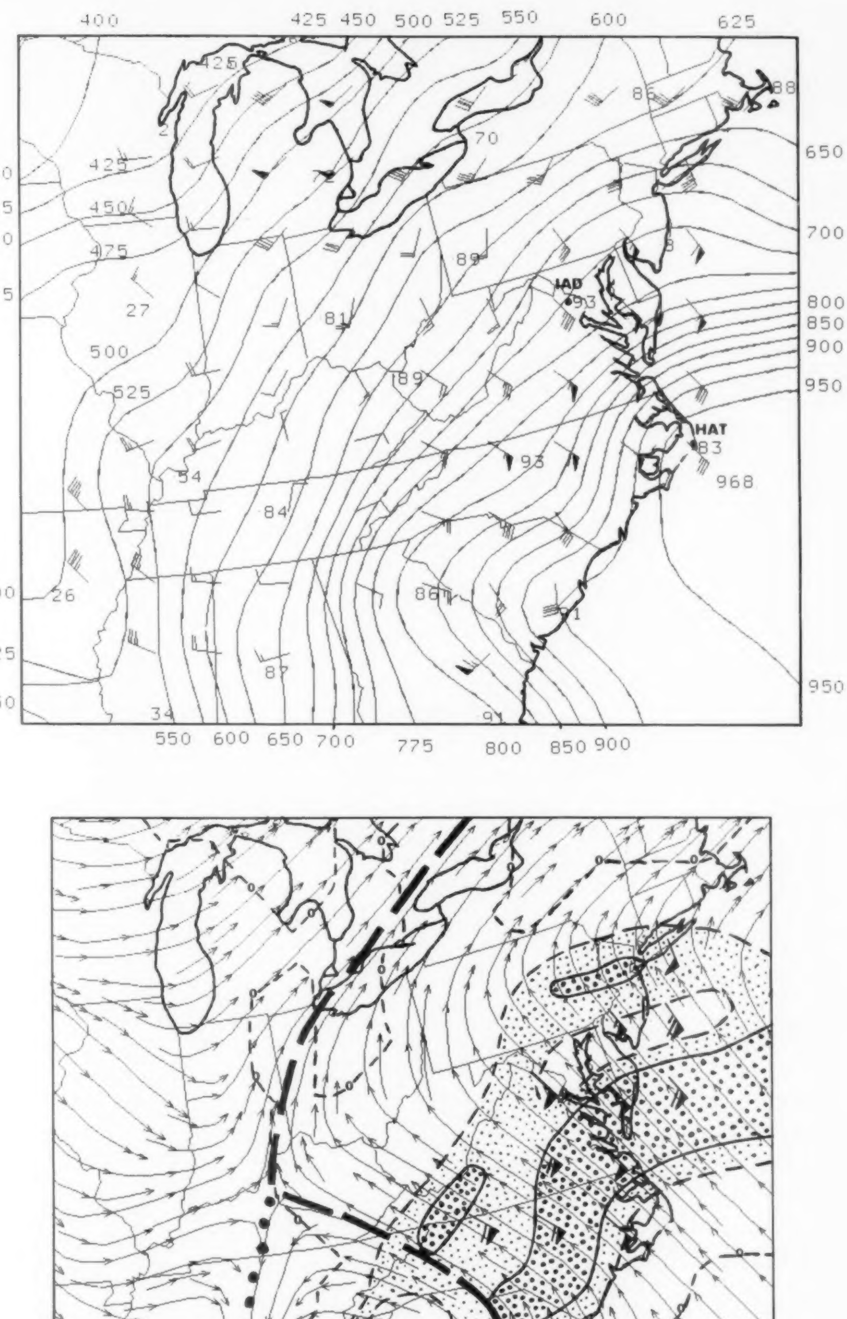

Figure 9. Isentropic analyses on the 293 K surface at 1200 UTC on 13 March 1993. (a) Pressures and relative winds. A movement of the isentropic surface from the ESE at 9 kn has been subtracted from the observed winds, representing the speed of movement of the coastal/warm front. Numbers indicate relative humidities with respect to liquid water at rawinsonde sites. (b) Streamlines of the observed winds, and wind barbs showing the area with wind speeds in excess of 50 kn. Areas with upward vertical velocity are shown, with light stippling where vertical velocities are 5–10 microbars s^{-1}, and heavy stippling where greater then 10 microbars s^{-1}. Heavy dashed line depicts limiting streamline separating moist flow off the Atlantic from dry continental polar air. Heavy dotted line represents deformation zone near the cyclone centre where bent-back warm/occluded front or frontal 'T-bone' is forming aloft.

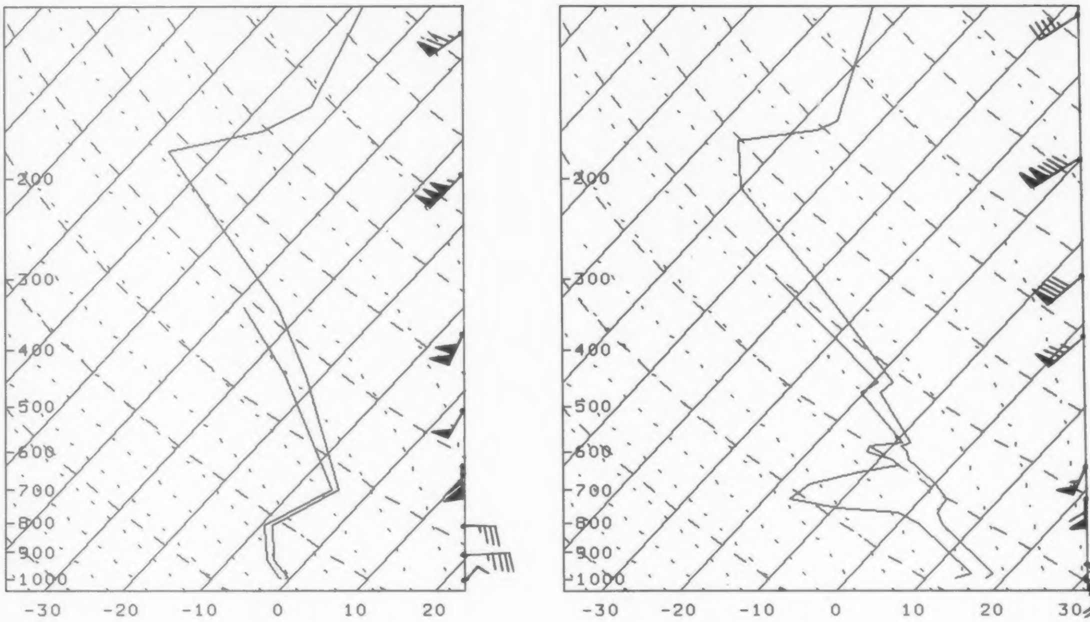

Figure 10. Soundings, skew *T*-log *P*, from (left) Cape Hatteras, North Carolina (HAT on Fig. 9(a)) and (right) Washington, DC Dulles International Airport (IAD on Fig. 9(a)) at 1200 UTC on 13 March 1993.

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Understanding the North Sea System

Preface

On 4 and 5 November 1992 a scientific meeting on 'Understanding the North Sea System' was organized by, and held at, The Royal Society. What follows was prepared after the meeting by The Royal Society and The Association of British Science Writers, to summarize key issues raised by the speakers. I am indebted to Dr S.J. Foreman of the Meteorological Office for contributing additional comments and explanations and to Valerie Doodson of the Proudman Oceanographic Laboratory for the chart and trapping a few residual errors.

This is the first of what I hope will be a series on ocean–atmosphere interactions: papers on sea-ice, wave modelling, and sea-level are being prepared for later this year.

Introduction

The North Sea is but a puddle compared to the world's mighty oceans. But to the countries around it, and Britain in particular, it is a source of food, energy and recreation as well as a sink for all manner of waste. It was therefore appropriate that scientists embarked, in 1988, on a project to understand the North Sea more thoroughly and in more detail than any large sea has been understood before.

The North Sea is a shelf sea — that is to say it lies not over the thin crust of the deep ocean but what is essentially a submerged continuation of the European continent. It is possible that convection in the Earth's mantle at about the time that the North Atlantic opened almost caused an ocean to open up where the North Sea now is. The result was a stretching of the earth's crust so that the upper surface sagged and filled with sediment and the

underside rose bringing heat up to bake the sediments, maturing reserves of oil and gas in the process.

Today, an emerging realization of the practical and economic importance of the Sea is coupled with concern about the health of the environment of these waters. In order to understand the interactions of both aspects, scientists are faced with the challenge of discovering the processes which control that environment. The 'North Sea Project', a major research initiative managed by Britain's Natural Environment Research Council, aimed to gather enough information to be able to set up a model of the North Sea through which to reveal the impacts of agriculture and industry as well as natural processes, and to understand the consequences of our actions in the future. What has resulted is not a physical model of the sea but a numerical model in a supercomputer. All the processes are represented by calculations and by changing the numbers it should eventually be possible to work out the real changes that could arise as a result of political action or inaction.

Motivation for the North Sea Project thus came about both from strategic necessity and from a need for fundamental science. No sea, and particularly no sea so closely linked with land and human activity, can be considered in isolation. There are constant interactions through rivers and coastal discharges, from the air, from the underlying sediments and within the water column itself. Such processes were very poorly understood and the North Sea offered the possibility of combining new and fundamental scientific research with something that has a high profile in the public mind.

Inputs and outputs

The North Sea is an environment under pressure. It receives a huge input of what, to man, is waste but, to marine algae are nutrients: human and animal sewage and nitrates washed from well-fertilized fields. The River Rhine alone contributes about a million tons of nitrate every year and until recently that output has been doubling every fifteen years. The result is often good news for the marine algae or phytoplankton that use nitrate as food. With the summer sun to aid their photosynthesis they can multiply on a tremendous scale and sometimes, particularly along the Dutch and German coasts, produce great foaming blooms reminiscent of pollution by detergent. In theory these might consume all the oxygen from the water, leaving it anoxic. In practice, so far at least, the blooms are very localized and only slight oxygen depletion has been observed around the Dogger Bank and the German Bight, and that does not last long.

Algae in their turn are food for marine animals. They are grazed upon by microscopic zooplankton which in turn are consumed by tiny predators and so on, up the food chain to fish. But fish have been removed from the North Sea at a phenomenal rate. At present one fish out of three is caught every year (*poor thing! Ed*). The long-term result of that has not only been a decline in all fish, but also a change in the balance of species, from herring and halibut to fish such as sandling that are usually processed industrially into animal feed.

In 1988 the plight of the North Sea was given widespread publicity as a result of the death of hundreds of seals around its shores. Ironically, this was almost certainly due to an epidemic of viral infection and not directly to pollution, but it placed the North Sea Project, which began in the same year, centre stage.

The North Sea Project

For fifteen months between August 1988 and October 1989, the Royal Research Ship *Challenger* (Fig. 1) worked exclusively on the North Sea Project, sailing a 3200 km course around the southern North Sea every month. Each circuit lasted for twelve days and RRS *Challenger* was able to visit up to 120 separate sampling stations. At each, instruments were lowered over the side and data were recovered from moored instruments. For the other half of each month, the floating laboratory concentrated her attention on studying specific processes in more detail: the physics and chemistry of the sea, the interactions between air, sea and sediment and the biology of the waters.

A series of special instruments was developed to accomplish this. Principal among them was a structure weighing a quarter of a ton and including sensors for temperature, salinity, dissolved oxygen, the chlorophyll in plankton and the clarity of the water, together with ultra-clean sample bottles that could be filled at different depths beneath the ship. It is a tribute to the crew of RRS *Challenger* that they deployed this at most stations, even in gale-force winds.

Another essential instrument was Seasoar, a device resembling a small, stubby-winged aircraft that could be towed behind RRS *Challenger*. Thanks to special hydrodynamic faring on the towing cable, Seasoar could be used whilst the ship was cruising between sampling stations at her full, if leisurely, speed of 9.8 knots. By angling the 'wings', it was possible to steer Seasoar up and down to take measurements at different depths. Perhaps most valuable of all, though less obvious, was the simple fact that all the measurements were carried out from the same ship with the same instruments calibrated to the highest standards, so the results could easily be combined into a single comprehensive database on the North Sea. Those processed data are now available internationally on a compact disc.

The dynamic sea

In the south, the North Sea is typically no more than 40 metres deep. In the north it can be deeper than 100 metres. That is deep enough to cause complex problems for divers and oil companies installing offshore production platforms, but to an oceanographer it is shallow indeed. The North Sea is also almost entirely surrounded on three sides by land. Yet into that enclosed basin comes a huge input of energy. The tides supply about 50 gigaWatts. That is roughly the total electricity

Photograph by Terence Soames (Cardiff) Ltd

Figure 1. RRS *Challenger*.

consumption of the whole of the United Kingdom. It is manifested not only as the twice daily rise and fall of sea level but also as a powerful stirring force. It lifts sediments and mixes chemicals through the water column. At the same time, the sea surface is also stirred by the wind.

Energy also comes from above as the sun warms the surface, particularly in the summer. That tends to make a layer of warm water develop at the surface. Because this warm water is less dense than the body of the sea below, it stays there. This kind of layering is known as thermal stratification. Further stratification can arise from salinity. In the North Sea, there is a constant battle between the sun's energy causing stratification and tidal energy mixing the water up. In the north, the sun wins and the surface of the sea remains comparatively warm and unmixed. In the south, tidal energy mixes the entire water column so the sun must heat more water and surface waters are cooler. The mixing in the south also stirs up more sediment so the water is less clear. That stirring process, together with input from rivers in the south, makes more nutrients available to stimulate algal growth.

Where the stratified northern waters and the mixed southern waters meet, they form a front, a region of sharp horizontal temperature gradients similar to fronts in the atmosphere. During the North Sea Project, RRS *Challenger* sailed to and fro across one of these fronts which typically runs down the Yorkshire coast and then across from Flamborough Head towards The Netherlands. Complex eddies can develop along it and biological activity in the form of plankton rises and falls depending on the temperature, clarity and availability of nutrients. In some places warm, clear water from the north and nutrients from the south provide just the right conditions for a bloom of phytoplankton such as coccolithophores.

The tidal rise and fall in the North Sea due to astronomical effects was predicted last century by Lord Kelvin and is one of the easiest things to model numerically. More recent models include the effects of the wind and are accurate to less than half a metre and regular predictions (from a model developed by the Proudman Oceanographic Laboratory (P.O.L.)) are issued by the UK Meteorological Office. Such models are also useful for tackling the harder problem of the fate of pollutants.

There is an overall anticlockwise circulation in the North Sea (see Fig. 2). Currents are fastest along the Norwegian coast where the maximum is about 13 km per day, but typically the flow is only a few kilometres per day and pollution can remain in the confines of the Sea for up to three years. During the North Sea Project, current measurements were taken from the ship, from moored instruments and by tracking free-floating buoys using satellite or radio navigation systems. There were mechanical current meters, acoustic Doppler current meters and radar current meters. Traces of radioactive caesium discharged from the nuclear reprocessing plant at Sellafield were tracked rounding Scotland and entering

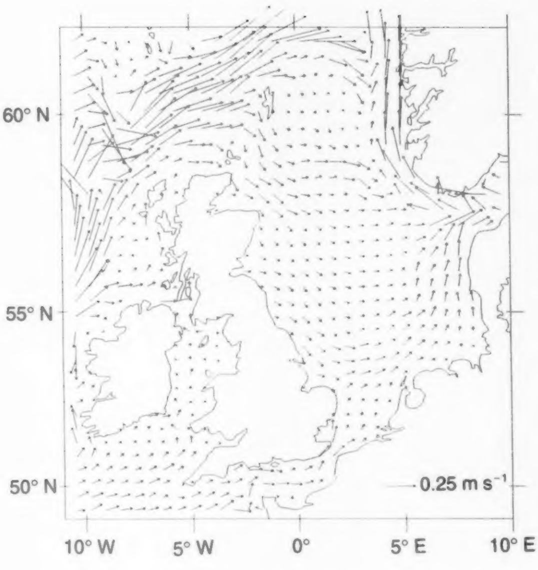

Figure 2. Mean surface currents (0–10 m depth) for January from a 3-D numerical model.

the North Sea. The flow through the Strait of Dover was monitored by radar from May 1990 to August 1991.

Vanishing sediments

The North Sea is muddy. It is not simply mud washed down in rivers. A large amount is stirred back into suspension from the sea floor or eroded from coasts. It provides a major constraint on the biological productivity of the waters by clouding them so that sunlight cannot reach algae far below the surface. The mud particles also perform important roles in absorbing chemicals such as metals and pesticide residues and thus remove pollutants from the water column. The sediments also store and release nutrients, continually recycling them into the marine environment.

One of the major surprises in the North Sea Project was the scale of sediment transport. At any one time in the summer there is about a hundred million tons of sediment suspended in the North Sea. In the winter, as gales whip up the waves and tides scour the bottom, the suspended sediment rises fourfold (the organic component remains roughly constant, the change is basically due to mud). The nett loser in this process is the British coast between Suffolk and Yorkshire, particularly the Holderness coast. Between them, they lose 6 million tons every year, most of which is transported across the sea towards the German Bight where it is deposited around the Friesian Islands. A lot of the pollutants are probably deposited here also, locked up in the sediments.

Interactions with the air

Rivers may supply most of the chemicals that enter the North Sea but a substantial quantity also comes from the air. The shallow sea with a large surface area, its waves and roughness, plus wind and rain all conspire to transfer soluble gases into the sea. If it were just a physical process, it would soon reach equilibrium with as much gas coming out of the sea as goes into it. But chemical changes take place which remove some of the dissolved gases from the balancing mechanism.

Carbon dioxide, for example, is taken out of solution by plankton which use it through photosynthesis to build their cells. They die, sink and decompose or are eaten by larger organisms. Eventually, a lot of the carbon gets recycled back to the atmosphere but some sinks to the bottom and is removed from circulation. During the North Sea Project, the scientists attempted to measure the rate at which carbon dioxide is removed from circulation. Before humans started burning fossil fuels and felling forests in large quantities, it is probable that the carbon cycle balanced. Now, we are releasing billions of tons of extra carbon dioxide every year. But it is not all remaining in the atmosphere and adding to the greenhouse effect. About half of the extra is somehow removed and it was assumed that the principal mechanism for this was through the microscopic plants in marine plankton. Measurements during the North Sea Project showed that this route only accounts for about 30% of the excess carbon dioxide. So perhaps processes on land, and in particular in forests, may account for more than anyone realised, making their destruction all the more serious.

The atmosphere supplies oxygen too; the oxygen that fish and other animals require, and the oxygen used as organic material decomposes. A fear that is frequently expressed in connection with the North Sea is that nutrients, such as nitrates and phosphates, washing into the sea from human activities, will stimulate the growth of plankton which will in turn die, sink to the bottom of the sea and decompose, using up oxygen from the water. In theory, that could lead to what is known as eutrophication — the water might become so starved of oxygen, at least at depth, that it becomes stagnant and smelly, changing the chemistry of its interaction with the sediments on the bottom.

That is already happening in parts of the Baltic where, each spring, organic material from the plankton blooms builds up below the surface and uses up all the oxygen. Since they cannot oxidise further, the nutrients remain suspended or dissolved in the water and if they were stirred up again by storms and brought back into the sunlight near the surface, they might not only create a stink but also produce a slime near the surface.*

During the North Sea Project, the scientists found that oxygen depletion was indeed occurring in the North Sea, on either side of the Dogger Bank and close to the coast of The Netherlands. But they doubt that a larger eutrophic zone is likely to develop because of the powerful tidal mixing which brings fresh oxygen throughout the water column.

* Readers wishing to learn more about air–alage–ocean interations are recommended the article in *New Scientist* of 21 August 1993.

The North Sea gives out gases as well as soaking them up. On the top deck of RRS *Challenger*, well forward of any contamination from the ship, was equipment from the University of East Anglia consisting essentially of lengths of plastic drainpipe connected to a vacuum cleaner. What it was actually doing was drawing the sea air in through a series of physical and chemical filters so that researchers could study traces of organic chemicals, metals and acid gases. Chemicals dissolved in rainwater were also analysed. One of the more surprising findings of this project was that the North Sea makes a considerable contribution to the problem of acid rain.

The phytoplankton breathe out dimethyl sulphide, a sulphur-containing gas which easily breaks down in the air into a variety of other gases, such as sulphur dioxide, and eventually gives rise to cloud condensation nuclei. These can dissolve in rainwater and fall as acid rain. The North Sea scientists calculated that the sea contributes as much as 25% of the sulphur that falls over Europe as acid rain. That still leaves three times as much coming from land, mostly from power station chimneys, so does not absolve humans of responsibility for acid rain. But it does mean that, however strict the curbs on man-made emissions, a residue will persist.

The dimethyl sulphide production is strongly seasonal, following the spring phytoplankton blooms. These are encouraged by nitrates washed out with sewage and agricultural run-off. So ultimately, human activity is at least partly responsible for this source of acid rain too. It illustrates how complex the interactions are both within the North Sea and between mankind's various activities.

A model for the future

The wealth of data from the North Sea Project has been fed into a Cray supercomputer by scientists at the P.O.L. The numerical model of the North Sea developed by P.O.L. now fits the observed facts with considerable precision. The horizontal currents, the vertical mixing, temperature, salinity, air and sediments are all represented. The aim is that, for any set of starting conditions, the computer will calculate how the real sea will develop. Once that is achieved, the scientists will have what they call a water-quality model. They will be able to program in various different political scenarios such as curbs on the use of nitrates or the discharge of sewage and see what their impact will be at sea.

The North Sea has a vast capacity for absorbing and treating the wastes we discharge into it, but that capacity cannot be infinite. At present, the great saviour is the natural stirring of the sea. It disperses pollutants and stirs up sediments so that light does not penetrate very deep, limiting phytoplankton to the surface. Thus they do not normally grow out of control in spite of abundant nutrients. The slimy froth of Phaeocystis plankton washing up on the shores of The Netherlands , and the eutrophication of water sheltered by the Dogger Bank are warnings that limits cannot be safely exceeded. Just what those limits are, and how the resources of our local sea can best be managed, should emerge from the computer models in the years to come.

The pioneering work performed on the North Sea will have applications far beyond our shores. Canada's Gulf of Maine, the Patagonian Shelf off Argentina and China's Yellow Sea are all examples of shelf seas to which many of the lessons learned in the North Sea will apply. Ultimately, even the best science will have to be supported with the political will to preserve the quality of such waters.

551.515.2:551.515.9(687)

Black south-easter havoc in Cape Town

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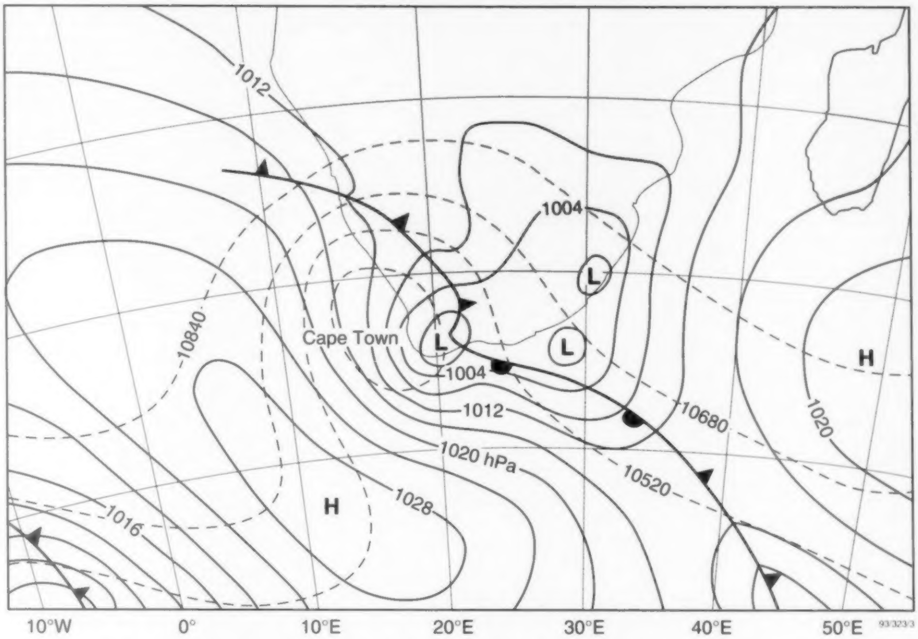
The extraordinary wind and rain condition that battered the Cape Town area during Easter 1993 was caused by the passage of a well developed cut-off low pressure system, locally termed a 'Black south-easter'. The prevailing summer 'south-easter' being a shallow wind associated with sunny weather.

A high (1016 hPa) in the area between Gough Island and South Georgia during 8 April started moving eastwards and a large amplitude trough approached Gough on the 10th setting up a strong meridional flow west of the high which in turn developed to a peak value of 1034 hPa late on the 10th.

Cold sub-polar air sourced in the Bouvet Island area was advected northward towards Cape Town and into a low (1002 hPa) off the South African west coast. This low was spawned and was well reflected passing an automatic weather station (AWS) in the Tristan Island group on the 9th.



Surface chart showing situation on 11 April 1993 at 1200 UTC. Dashed lines are contours (m) at 250 hPa.


The picture above, kindly donated by *The Argus* shows a wave breaking over the Kalk Bay harbour wall. Damage to the breakwater later allowed the waves to get into the harbour itself, and this led to the destruction of the wooden quay in the foreground.

The necessary energy became available to modify this benign low into a deep, cold-cored cut-off low. The low crossed the coast close to 32° S latitude early on 11 April and moved rapidly southward to exit off shore east of Cape Town in the Cape Agulhas area, during the afternoon of the same day with a central pressure of 999 hPa. Strong gale force SSEly winds spread rapidly over the area from the south. One coastal AWS close to Cape Town showed a jump of 22 knots between hourly averaged speeds.

Large topographically induced differences in wind speeds around the Cape Peninsula are well described (Jury 1980). The Port Captain's log noted a gust of 94 knots late on the 11th in the Table Bay Harbour area (anemometer atop a 14-storey building). Under deep SSEly wind conditions the harbour coincides with an area of extreme turbulence where a mountain wave returns to the surface downwind of Table Mountain. Press reports naturally latched onto this sensational value. At the D.F. Malan Airport, hourly averaged winds reached 39 knots gusting to 58 knots.

Cut-off low pressure systems of this intensity are well known to deliver localized extreme amounts of rainfall over the sub-continent. Taljaard describes 11 systems per annum with 1 in 5 causing flooding (Taljaar 1985). The rainfall is induced by vertical motions associated with surface convergence and upper divergence. Local orographic uplift was also a major contributory factor in this case.

Rainfall measured at the airport showed the highest 24-hour total on record on the 11th, namely 96 mm. The previous record standing at 65 mm in May 1974. Two of our rainfall stations situated close to the Franschloek Mountain range recorded 24-hour totals of 150 mm.

A wave-rider buoy on the western side of the Cape Peninsula recorded an increase of 5.5 m in wave height in 9 hours to 1500 UTC on the 11th, to peak at 7.76 m (Hmo), 13.5 sec.

False Bay is a traditionally safe refuge from the winter NWly gales but this abnormal wind driven sea wrecked many fishing and pleasure craft. A wooden quay and part of the sea wall in the Kalk Bay fishing harbour were very badly damaged. The rapid onset of wind caught a fleet of dinghies unprepared in Saldanha Bay. Their regatta was abandoned while rescue craft were kept very busy.

One Cape Town morning newspaper ascribed 12 deaths to this storm, the other, 6. Flooding and road wash-aways were the order of the day while electrical power lines were cut in many areas. At the airport, wind-driven rain from this quarter penetrated the instrument landing system and caused it to malfunction. Air traffic was halted for the night. Local press reported this as the first airport closure in 26 years which resulted in 27 aircraft diversions and 2400 delayed and irate passengers.

Computer model predictions gave ample warning of the excessive wind and rain early on the 10th (Saturday). Local forecasters were most concerned with the possible disruption of home-coming Easter weekend road traffic which is traditionally very heavy. The worst of the storm, however, passed during Easter Sunday afternoon and evening and it was only mopping-up operations which hindered home coming holiday makers.

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Taljaar, J.J., 1985: Cut-off lows in the South African region. Technical paper No. 14, Weather Bureau, Pretoria.

551.593.653(4):551.506.1

Noctilucent clouds over western Europe during 1992

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Summary

Noctilucent cloud observations by professional and amateur observers in the British Isles, Denmark and the Netherlands indicate a very low incidence in 1992.

Table I summarizes the noctilucent cloud (NLC) reported to the Aurora Section of the British Astronomical Association (BAA) during 1992. The times (UT) are the reported sightings limits; not necessarily the durations of the displays. 'Negative' nights (Table II) are based on the judgement of two or more experienced observers north of 54° N with clear or nearly clear sky conditions over the period of the night when NLC is likely to occur.

Only 12 definite NLCs were reported with four 'suspect'. Only one, on 21/22 June, was a major display: from simultaneous parallactic photography by Dr Simmons (Milngavie, Glasgow) and Dr Gavine (Joppa, Edinburgh), Dr Gadsden calculated a height of 81.9±1.0 km. Contributions were received from 15 voluntary observers and three meteorological stations in the British Isles, five excellent observers in Denmark and two stations of the Royal Netherlands Meteorological Institute, but there is still a shortage of observers in the rest of Europe. The Finnish–Estonian NLC sightings continue to be published annually in the journal *Ursa Minor* of the URSA Astronomical Association, Helsinki. Details of individual nights, and observing instructions,

are available from the author, but all NLC data up to 1990 are held in the Balfour Stewart Archive at the University of Aberdeen. To avoid confusion it would be appreciated if observers use the 'double date', e.g. 21/22 June, the night of the 21st and morning of the 22nd, and log all times in UT. It would also be useful for more observers to log 'negative' nights.

Our thanks to all observers, amateur and professional, and to the following for their support and co-operation: Mr Ron Livesey (BAA Aurora Section Director), Mr Tom McEwan (Junior Astronomical Society Aurora Section Director), Mr Veikko Makela (URSA, Finland), Dr Balthus Zwart (Netherlands), Mr Mark Zalcik (USA–Canada Network) and Dr Michael Gadsden (University of Aberdeen).

Table I. Displays of noctilucent clouds over western Europe during 1992

Date — night of	Time UT	Notes
2/3 June	2227, 0200	NLC band suspected at Aberdeen and a possible pale horizontal form in a poor sky at Witham, Essex, at 0200, but no NLC visible in clear skies in Stirling, Ayrshire and Denmark.
9/10	2315–0152	White opalescent veil up to elev. 20° at Kinloss, brighter 0045; very faint bands up to 15° at Alness, suspected faint veil at Witham. No NLC visible in Denmark up to 2245 then faint bands at Tisvildelege at 2315.
10/11	2325–0150	Mr Fraser at Alness observed faint bands in NE up to 25°, Kinloss met. station saw faint 'silvery streaks' up to 20°. No NLC visible at Morpeth or S of Scotland, nor Denmark.
14/15	0100–0200	Bands and billows noted by a single observer at Kemnay near Aberdeen but no NLC visible in clearing sky in Ayrshire 0045–0140.
16/17	2345–0115	Suspect diffuse bands in haze in Ayrshire but negative reports from Alness, Milngavie, Morpeth and Denmark.
18/19	0130–0200	Possible NLC in trop. cloud breaks at Glengarnock, Ayr, 0130, definite bands above cloud bank at 25° from 0145.
19/20	2330–0050	No NLC at Vildbjerg (Denmark) up to 2300, moderately bright billows up to 20° at Greve at 2330, bright bands up to 40° at Copenhagen 2345–0050.
20/21	2330	Mr Olesen at Rønne (Bornholm) detected bands up to 15° in a moonlit sky. No NLC at Morpeth but sky conditions deteriorating.
21/22	2130–0245	Bright and extensive display, all forms, reported and photographed from Moray Firth to Isle of Man whose observer noted that it was the brightest he had ever seen. Blue-green colour reported at Milngavie. NLC visible in zenith at Vildbjerg (Denmark) 0100, Morpeth 0200, and in Ayrshire reached altitude 120° at 0215.
26/27	2250–0100	Moderately bright bands observed from North Wales, Isle of Man, Whithorn and Morpeth. At 0005 Mr Young in Dundee saw billows and whirls, white and gold, up to at least 20° in trop. cloud gaps. No NLC visible at Witham and Bornholm.
2/3 July	2230–0035	Mr Andersen at Vildbjerg photographed veil and bands up to 18°. No NLC visible at Stirling, Copenhagen and Bornholm.
3/4	0220–0235	Bright billows in trop. cloud gaps at Glengarnock. No NLC in broken trop. cloud at Bornholm 2115.
8/9	0000	Suspect faint band very low at Stirling. No NLC in clear sky at Milngavie or Glengarnock 2230–0215.
20/21	2110–2340	Veil, bands and billows up to 10° in trop. cloud gaps with bright moon, photographed at Bornholm. No NLC in mainland Denmark. Fair Isle met. station reported one okta of billows up to 20°.
21/22	2155–0130	Bands up to 20° observed at Morpeth and St Andrews, photographed by Mr Whipps at Consett.
22/23	2150–2325	Fairly bright display of bands with some billows and whirls up to 10°, observed at Bornholm and Vildbjerg. No NLC visible in deteriorating sky at Morpeth.

Table II. Negative nights (British Isles and Denmark) north of latitude 54° N

May 25/26, 26/27, 27/28, 28/29; June 1/2, 3/4, 5/6, 6/7, 7/8, 8/9, 11/12, 15/16, 23/24, 24/25; July 4/5, 5/6, 6/7, 7/8, 10/11, 14/15, 25/26, 26/27, 28/29, 29/30, 30/31; August 3/4, 4/5 .

551.5:06.(b):65

The management of change. Case-study — the commercialization of the UK Meteorological Office

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Summary

This paper presents a case-study of the management of the change towards commercialization by the United Kingdom Meteorological Office during the period 1984 to 1992.

1. Introduction

The UK Meteorological Office successfully integrates a broad range of meteorological activities, research and operational tasks, as well as the provision of services to a very wide range of users. These include the armed forces, national and international civil aviation, universities, institutions, organizations in both the public and private sectors, as well as the general public. On 31 March 1991, it employed 2490 staff, and had an annual expenditure in 1990/91 of £107 million. The present-day Meteorological Office, a part of the Ministry of Defence, is modern, effective, and in the forefront of world meteorology. Forecasts are consistently accurate to well above the 80% level, and it speaks with authority on major issues concerning the environment — the ozone layer, pollution and global warming.

In 1984, an independent review (called the Resource Control Review) recommended greater commercialization of existing services of the Meteorological Office as a way of improving the use of its resources. As part of this, marketing disciplines were developed and applied to the Office's revenue-earning activities. This commercialization process advanced steadily until the present day. In April 1990, the Meteorological Office became an Executive Agency. As both owner and principal customer of the Meteorological Office, the Ministry of Defence has now given the new Agency much more challenging targets than in the past, and a far greater emphasis on developing its customer–supplier relationships.

2. First steps

Services attracting payment have been offered to parts of commerce and industry for many years. Initially they were forecasts or climatological data summaries that were priced at levels which have now come to be regarded in the United Kingdom as very low. The background of the organization as a public service created a widespread and even passionately held belief among staff that all users of meteorological services should be given the best possible information even where the price charged was below cost. Thus the quality of service was seen to be measured almost entirely by the accuracy of the data supplied; little effort was given to enhancing the presentation or delivery of the services. The needs of customers were generally assumed to match this view, and customers, knowing little better, tended to accept what was offered.

Following the recommendations of the Resource Control Review in 1984, the Office established a Marketing Branch, and a Steering Group was set up to direct the development of commercial activities in the Office. Little clear guidance was available about how to develop from a public service into a commercial organization, and there was only partial commitment at the most senior levels. This was reflected in a general reluctance to adopt new business practices and marketing disciplines, and a tendency to rely upon the established wisdom that we already knew what customers wanted.

There was an initial burst of undirected market research and opportunistic development of commercial activities. This period was very valuable in gaining experience and understanding about markets, and in testing the theoretical marketing models offered in training courses. However, it led to several failures and little real market development. Several marketing consultants were brought in to assist with the problem; their advice was very variable in quality. The best advice was to base a market development strategy on information from an initial in-depth interview survey of a range of existing users, together with the information about customers that was already available within the Office. Much of this information was qualitative, but it provided a workable basis for identifying the major market opportunities at that time. The strategy created was to develop each market opportunity in turn, starting with the one most likely to achieve success. As each of these came to fruition, great care was taken to give the success to other involved management areas and not the Marketing Branch, even where it was initially responsible for the development. If successful, this would not only

provide credibility within the Meteorological Office for marketing techniques, but would also help to encourage managers to address the organizational problems of commercialism.

3. Development

Up to 1990, when the Meteorological Office was made an Executive Agency, the commercial development was slow, but it followed the proposed strategy. However, the subjective day-to-day experience of many staff seemed very different. Enthusiasm for a more commercial way of doing things was very patchy, often found in individuals rather than in groups, and it often had little clear direction. New products were invented and launched without any reference to the customers they were supposed to reach, and market research was conducted in an *ad hoc* manner, with little attempt to put the results into some overall context. Customers were fitted into functional categories ('customers for forecasts', 'customers for climatological services'), so that many of them had to get the information they wanted from different parts of the Office. Commercial procedures were not consistent across the organization — some customers would contact several weather centres in order to get the cheapest price for a service.

Despite all this, two fundamentally important points emerged.

(1) People began to learn through their own experience and the experience of others. Even negative experiences were incorporated into the corporate body of thinking as examples of 'how not to do something'. This learning process was at the heart of the change in culture that has been observed, and was an absolute precondition for the rapid changes that followed the creation of the Executive Agency.

(2) The major part of the early growth in commercial revenues came from the simple process of telling people about the Meteorological Office and its services. This was done in many different ways, but with little overall coordination. Newspaper articles, television interviews, talks and lectures, information sheets and brochures, telephone conversations and face-to-face meetings occurred, often initiated by enthusiastic individuals, but all were characterized by an excitement with, and belief in, the services being offered by the Office.

4. Organizational changes

As the credibility of the commercial approach improved within the Meteorological Office, so it was possible to implement changes to improve the organization of commercial activities. A programme of commercial training for all staff was developed. This was aimed not only at improving skills, but also at creating a commitment to a commercial philosophy and to identify commercially oriented staff who could be moved into more influential positions. Financial and information systems were gradually modified to match the segmentation of customers that had been developed, and to link the revenue generated by a service, or by a group of customers, with the associated costs. In this way there was a gradual change away from maximizing revenue as the principal commercial objective towards the objective of maximizing profit.

Before 1990 the most significant structural development was the introduction of two Business Units. These were created in response to market information that showed that many customers needed services from more than one functional area in the Meteorological Office, they wanted to deal with only one point of contact and they wanted to speak to staff who understood their problems and who spoke in terms they could understand. Business Units were set up to serve the Retail Industry and the Television Industry.

5. Developing a commercial culture

The fundamental problem of commercialization of the Meteorological Office has been the creation of a commercially oriented culture. When the Meteorological Office started to develop its commercial activities, there was a general suspicion that such a culture was in some way 'immoral' and that it would cause standards of quality to drop. Feeding these suspicions was the possible threat of job losses in the future.

Managing such a radical culture change requires leadership skill and considerable patience; people cannot readily be programmed, and they take time to change their views. In essence, it involves encouraging staff to change their viewpoint in a positive manner, and removing obstacles to such changes.

Several methods used to encourage staff to change their views.

(a) *Involvement in the commercial process.* Staff who felt they were a part of a new initiative, and whose ideas were listened to invariably were among the first converts.

(b) *Conferring success.* Although most of the early successful developments were initiated within the Marketing Branch, great trouble was taken to confer the success to other managers in other sections. A good example is the launch of the new 'OpenRoad' package of services to the highways departments of local government where, following about two years of Market Research and product development, the Weather Centres were assisted in selling the new service. Sales materials and marketing consultants were provided. The success of the venture was a great boost to the pride and motivation of staff in the outfield.

(c) *Training.* Training courses were aimed at improving the skills and motivation of all staff.

(d) *Leadership.* Leadership within the commercial sections of the Meteorological Office tended to occur spontaneously in a few individuals, and was not treated by senior directors as a particularly important factor in the development of a commercial culture.

Management has now developed leadership teams in each business area.

(e) *Having a clear mission.* Coupled with the lack of concerted leadership was the initial absence of any clearly understood and accepted mission statement, which expressed the basic purpose of the organization and the values that the organization expected every member of staff to share. This shortcoming has now been rectified with the Chief Executive's Charter Statement, published in 1993. It is headed:

**Our purpose is to excel
in providing meteorological services
that meet our customers' present and future requirements.**

6. Maturation

Following a long period of development, the change to Executive Agency was relatively straightforward; all that was needed was to organize and direct the changes that had already taken place. A restructuring occurred to bring all of the commercial activities under one director, and organized in a conventional business structure: Marketing, Sales, Production, Product Development and Administration. Within the Sales Division, each major market sector is served by a Business Unit, responsible for serving the complete range of needs of their customers. The old, functional divisions have mostly disappeared.

The success of this strategic approach to the management of change can be seen in the rapid growth in revenue from services to the major market sectors: land transport, premium-rated telephone services, services to Television and so on. In the five-year period from 1984 to 1988 commercial revenues doubled (from about £4 million to £8 million), and it is predicted to double again (to £16 million) by 1993.

7. Conclusion

The development of commercialization within the UK Meteorological Office has taken place over a period of nine years, and the process continues. There is, however, a long way still to go.

Change has not come quickly. Those made responsible for the changes were advised that it would take years, not months. It has been a long and frustrating process for all involved, and there were mistakes made in the earlier years that may have caused the changes to be even slower in maturing.

However, despite the mistakes and false starts, the Meteorological Office has been profoundly successful in its change to commercialization, and the Commercial Services Division now enjoys an equal status with the other major divisions, and plays a vital part in securing funds for the continuing operation of the Office as a whole.

Books received

Inverse methods in physical oceanography, by A.F. Bennett (Cambridge University Press, 1992, £35.00, $59.95) explores the potential for inverse theory in oceanography, emphasizing possibilities rather than expedient or rudimentary applications. Ocean models considered range from linear, finite-dimensional systems of equality and inequality constraints to non-linear, regional primitive-equation models. Exercises of varying difficulty rehearse technical skills and supplement the central theoretic development. ISBN 0 521 38568 7.

Climate system modeling, edited by K.E. Trenberth (Cambridge University Press, 1992, £35.00) provides a thorough grounding in climate dynamics and the issues involved in predicting climate change. It not only discusses the primary concepts involved but also the mathematical, physical, chemical and biological basis for the component models and the sources of uncertainty, the assumptions made and the approximations introduced. This is a comprehensive text which will appeal to students and researchers concerned with any aspect of climate and the study of related topics in the earth and environmental science. ISBN 0 521 43231 6.

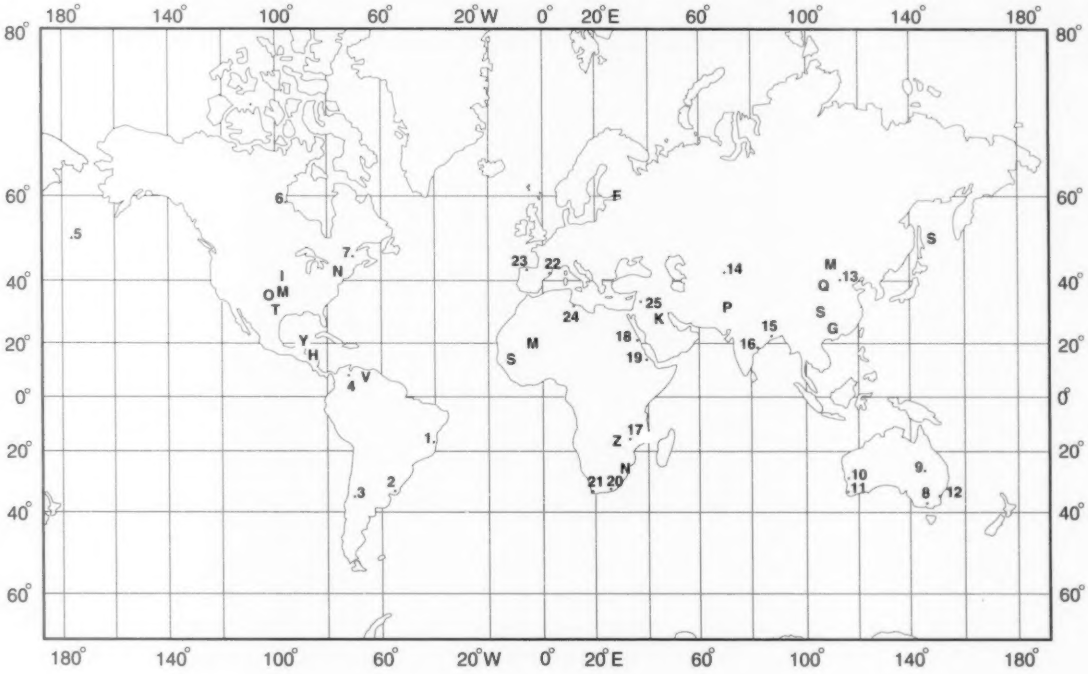
El Niño — historical and Paleoclimatic aspects of the Southern Oscillation, edited by H.F. Diaz and V. Markgraf (Cambridge University Press, 1992, £40.00) examines for the first time different approaches to reconstructing ENSO based on a variety of proxy sources, ranging from high-resolution environmental indicators such as tree rings etc. to records on the impact of ENSO on fisheries and marine and lacustrine sediments, to a long record of vegetation changes in the southern hemisphere. This book will be of importance to all professional scientists and researchers in climatology, meteorology and the earth and environmental sciences, while graduate students will also find this book a useful reference source. ISBN 0 521 43042 9.

The atmospheric boundary layer, by J.R. Garrett (Cambridge University Press, 1992. £50.00, $79.95) is intended to be an advanced graduate level text and a reference book for practising meteorologists and atmospheric scientists. The emphasis is placed on surface processes and the application of atmospheric boundary-layer problems to the modelling of climate. ISBN 0 521 38052 9.

World weather news — April 1993

This is a monthly round-up of some of the more outstanding weather events the month, three preceding the cover month. If any of you, our readers, has first hand experience of any of the events mentioned below or its like (and survived!), I am sure all the other readers would be interested in the background to the event, how it was forecast and the local population warned.

These notes are based on information provided by the International Forecast Unit in the Central Forecasting Office of the Meteorological Office, Bracknell and press reports. Naturally they are heavily biased towards areas with a good cover of reliable surface observations. Places followed by bracketed numbers, or areas followed by letters, in the text are identified on the accompanying map. Spellings are those used in The Times Atlas.



Location of places mentioned in text

South America

Linhares (1) in Brazil is our first report of heavy rain — 110 mm in a thunderstorm on the 3rd: Santa Vitoria do Palmar, near Montevideo (2), followed with 168 mm on the 3rd/4th with 86 mm in a 6-hour period (the April average is 74 mm). A depression crossing Uruguay over the period 3rd to 7th deposited 161 mm in Montevideo (April average 99 mm) and well over 50 mm elsewhere. Santiago (3), Chile, broke its half-year drought on the 13th when 15 mm fell; by the 20th the total had reached 77 mm (the April average is 13 mm).

The heat around the Gulf of Mexico reached Colombia on the 16th when Cucuta (4) broke its April record in getting to 37 °C. The country suffered flash flooding on the 26th with between 50 and 100 feared drowned in Los Andes 75 miles from Medellin, and along a 220 km stretch of the river Cauca. In three days starting the 25th Quibdo measured 152 mm; further east at Villavicencio, south-east of Bogota, got 238 mm.

North and Central America

On the 6th a Chinese Eastern Airlines MD-11 aircraft encountered severe turbulence over the Bering Sea, one passenger was killed and 50 injured, and the aircraft was forced to make an emergency landing at Shemya (5) in the Aleutian Islands.

Spring arrived with April in the Canadian province of Manitoba; Churchill (6) recorded +6 °C on the 4th, about 13 °C above the average.

Flooding occurred at the beginning of the month in Iowa (I) as 50 cm of snow pack started to melt in heavy rain. These floods gradually spread south, and by the 12th the Mid-West was reporting problems as the upper

reaches of the rivers Mississippi and Missouri flooded over wide areas. Waterway traffic was badly affected by strong currents and locks being closed to control the flow. Problems reached their worst about the 23rd and started to ease at the very end of the month.

There was a stream of reports of high temperatures from around the Gulf of Mexico, one of the first was Campeche, Yucatan (Y), with 37.7 °C on the 7th (April average is 31 °C). Choluteca in southern Honduras (H) reported 40.0 °C on the 8th and many observers in north-west Venezuela (V) were reporting 35–40 °C on the 10th. Merida, Yucatan, had 37.8 °C on the 14th; on the 25th a new record was set when 39.5 °C was reached.

On the 19th there was a 'a catastrophic' storm of wind and hail in Texas (T) and Missouri (M) with tornadoes. Details are scarce but insurance claims are running at $60m due to damage to skylights, roofs and cars. Something similar happened five days later on the 24th in Tulsa, Oklahoma (O), ten were killed by tornadoes that struck late in the day, funnel clouds skipped but touched down to obliterate two truck stops on Interstate 44, seven miles of which were closed for a time while debris was cleared. Sirens were only able to give a few minutes warning and 140 homes were damaged.

An ordinary winter storm occurred on the 22nd and dumped 15 cm of wet snow on Pennsylvania and New York State (N) at low levels: over the maritime provinces of Canada about 30 mm of rain fell. A secondary low to this system brought strong northerlies on the 25th and caused a storm surge on Lake Champlain, south of Montreal (7), putting a metre of water into the shore towns.

Australasia

This information is largely based on that kindly given by the Australian Bureau of Meteorology.

Persistent high pressure systems near south-eastern Australia in the second half of the month produced very warm and dry weather over the eastern half of the continent except the tropical coast of Queensland (QLD) and the south coast of New South Wales (NSW). In many places it was the warmest and driest April on record. Among the new record mean maxima were Melbourne (8) with 23.1 °C (previously 22.9 °C set in 1865) and nearby White Cliffs 30.0 °C (29.8 °C in 1922) and Windorah, QLD, 33.1 °C (32.8 °C in 1953). Although it was not the first rainless April for many stations, there were some that had not had one since 1923. At the other extreme, Geraldton (10) in Western Australia (WA) equalled its previous lowest April maximum with 18.9 °C on the 30th. In the rainfall stakes Cape Leewin (11), WA, took the palm with a new April daily record of 88.4 mm on the 30th (previously 68.8 set in 1913). The most notable thunderstorm of the month occurred on the other side of the continent when late on the 5th, Canberra (12) got 18 mm of rain and hail in 20 min with a gust to 56 kn: this caused much damage to property, trees and power lines.

Asia

During the first week of April Sakhalin Island (S) had a 'cyclone' which is quoted to have dumped two months' rain and snow on the island and brought most transport to a stop. Possibly related, on the 3rd, the town of Zhangjiakou 100 miles north-west of Beijing (13), found the previous day's maximum of 16.2 °C had been followed by a minimum of −0.2 °C with snow. The Chinese province of Quinghai (Q) had 'severe snow storms that have buried an area the size of Norway since January'. This is a sparsely populated area but thousands of head of livestock died and many thousands of people suffered frostbite and snow blindness and expeditions were dispatched to help out. In Mongolia (M) there were reports of devastating snow storms on the 15th which had killed more than 13 humans and more than half a million livestock. The storms are said to have been the worst for 30 years with huge drifts in mountainous areas, help was required to dig people out. In contrast Beijing broke its April record when the temperature reached 32.1 °C. A few days later on the 24th, in the Chinese province of Sichuan (S) there were reports of hail and gales which combined to kill 31 people and injure 379, destroying 30 000 houses in 11 cities: the cause of this disaster is not clear. Further heavy thunderstorms, with hail, were reported to have caused widespread damage on the 25th throughout Guangxi (G) province. They killed 18 and injured 300. The rain lasted for two days and about 400 homes were destroyed. It seems likely that this mayhem was connected with the collapse of a heat-wave that had been affecting much of central Asia up till then. As a single example, Tashkent (14) had a maximum of 28 °C on the 23rd but only 6.5 °C on the 24th.

On the 22nd Mount Sheveluch in Kamchatka erupted spectacularly after being dormant since 1964. However I have no reports of how high the dust was ejected. Japan had problems on the 29th when heavy rain fell on the sides of the active volcano Mount Unzen, and the resulting debris and mud (lahar) washed into nearby rivers, causing a lot of flooding.

Indian subcontinent

West Bengal suffered tornadoes on the 10th when more than 100 were killed in Murshidabad, 100 miles north of Calcutta. Apparently this is quite a rare occurrence in India. The casualties seem to have included some 2000 head of cattle and reports speak of two lorries and a van load of people being hurled hundreds of metres into the middle of a rice paddy and drowned. Many newly installed power lines were blown down and trees uprooted. Ponds became contaminated by bodies and carcasses of cattle. The 12th and 13th gave some thunderstorms in Orissa, the town of Bhubaneswar (16) got 62 mm (monthly average 41 mm) and Jamshedpur 40 mm (average 25 mm). As the month wore on temperatures rose (on the 28th Hissar in the Punjab (P) reported 45.7 °C) but a sinister development was heavy, thundery

rain in north-east India and Bangladesh with falls of nearly 100 mm in several places over the last day or two of the month (see this space for June).

Africa except the Mediterranean coast

We open on a hot note: in Senegal (S) temperatures were near record values on the 9th when 43.6 °C was reached. On the 12th 42.5 °C was reached at Segou on the banks of the Niger in Mali (M), that night some cloud moved in and the minimum was 30.4 °C! For much of the rest of the month maxima in western sub-Saharan Africa were between 40 and 45 °C. Further south in Zambia (Z) the rainy season is supposed to have been over, but a thunderstorm at Mongou dropped 106 mm (monthly average is 39 mm). A couple of days later, on the 14th, Bukoba on the shores of Lake Victoria collected 132 mm; Harare's (17) 54 mm (April average 39 mm) showed that the Zimbabwean rains had not yet ended.

In Sudan there seems to have been an unusually violent cold front around the middle of the month. The unusually heavy rain led to flooding which caused the deaths of up to 21 around Port Sudan (18) and put out of action a bridge on the vital highway to Khartoum; it also endangered the fresh water supply. About the same time thunderstorms were causing some damage further south in Eritrea rendering thousands homeless. Reports say that at noon on the 15th in Massawa (19) winds suddenly reached 70 kn from the north for 45 minutes and this was followed by heavy rain for another 45 minutes. The town was flooded, the port installations damaged. Dockside cranes were blown along their rails at more than their maximum design speed, this caused gearing to overheat and burn out clutches.

The month came to a hot close in Niger; N'Guimi raised its April record by one and a half degrees to 45.6 °C; in the Sudan a new April record was set at Karima with 47.0 °C.

The following notes are kindly supplied but the South African Weather Bureau.

In the first week a persistent trough in the west spread scattered showers eastward into Natal (N) on the 4th with some good falls of rain (75 mm at Underberg). A fast moving depression on the 5th/6th generated strong coastal winds with some damage to buildings and trees in Port Elizabeth (20). On the 11th one of the worst storms in 30 years crossed the south-west Cape with exceptionally heavy rainfall (153 mm at Villersdorp): at least eleven people were drowned in the subsequent flooding. The railway from Simonstown (21) to Fishoek was closed and the N1 was closed when a dam wall collapsed with considerable damage to the main breakwater jetty and many small vessels. (The meteorological background to this storm occurs elsewhere in this issue.) The cold front brought frost to the interior and light snow to the Drakensburg. Another deep low skimmed the southern Cape on the 16th/17th with gale force winds, showers over Cape Province, and hail damage near Colesburg. The second half of the month brought some settled weather in which Alexander Bay managed a maximum of 40.0 °C on the 21st but with ground frost in Orange Free State. The last cold front of the month on the 27th was followed by the coldest night when −1.6 °C was recorded at Buffelsfontein. April rainfall records were broken in Cape Town, Cape Agulhas and Port Nolloth. Although the rainfall was welcome, there was some damage to crops, and few surface water reservoirs were replenished.

Europe, North Africa and Arabia

Much of the month was cyclonic, with a tendency for many smaller lows rather than single monsters. The overall trend was for the south-west to be cool and wet, the south-east to be hot and the north averagely mixed. For a change a UK station starts the list of notable events; Middle Wallop weighed in with 40 mm on the morning of the 1st (monthly average is 54 mm); many other southern gauges followed suit with 30 mm or more. A different low was giving similar amounts of rain along the south coast of France along with a brisk mistral, Cap Béar (22) reached 55 kn with gusts to 62 kn. On the 5th the Swiss had their turn when over a two-day period high-level stations collected 70 mm and the lowlands more than 20 mm. The Easter holiday brought a real stinker to Aberdeen; an almost stationary front caused hours of gloomy south-east wind off the North Sea, a maximum temperature of 6 °C and 40 mm of rain.

The Gulf of Finland (F) was the scene of some excitement on the 8th when an unusually cold spell caused the formation of new ice flows just as the ice breaker returned to port for refuelling. Then on the 12th the vessel Vishva Mohini with a cargo of 1200 tons of heavy machinery had problems when heavy seas caused its cargo to shift in a force 7 easterly in the Bay of Biscay. The ship sank suddenly, but 16 of the 48 crew were rescued about 48 miles north of Cape Penas (23). A couple of the days later on the 14th there was a report of a tornado in San Tropez, yachts were sunk and trees were blown down and about £2m of damage was done.

Among the hot spots were Tripoli (24) 36.4 °C on the 11th, Iraklion, Crete, with 35 °C on the 13th, Tel Aviv 35.0 °C on the 14th; Damashq (25) 34 °C on the 16th (1 °C short of the record). Cairo's minimum of 29.2 °C on the 18th was 1 °C above the normal daytime value.

The cool, wet spots included the thunder-struck Balearics on the 14th where Mahon collected 23 mm. Calamocha in eastern Spain measured −3.5 °C and Majorca +2.8 °C on the very chilly morning of the 18th: in the narrows of the Strait of Gibraltar Tarifa was having a easterly gale with gusts to 43 kn (and 72 mm of rain on the 28th). The prize has to go the Mount Aigoual north of Nîmes, for 48 hours of the 26th and 27th they had persistent fog with thunder, hail, rain, sleet, snow and a gale with gusts to over 80 kn.

On the fringe of this area Arabia had a hot month, but most notable were the thunderstorms that swept south on

the 26th from Iran to Bahrain and Riyadh. Compare Kuwait's (K) 26 mm with the average of 13 mm, and Abadan (average 20 mm) had 34 mm on the 25th; next day another 24 mm fell accompanied by a squall to 52 kn.

Antarctica

On the 3rd McMurdo Sound collected snow to a rainfall equivalent of 15 mm (April average 25 mm) with a temperature of about −12 °C. On the 10th an AWS near the Pole reported a temperature of −67.9 °C, the Russians at Vostok managed −70.7 °C!

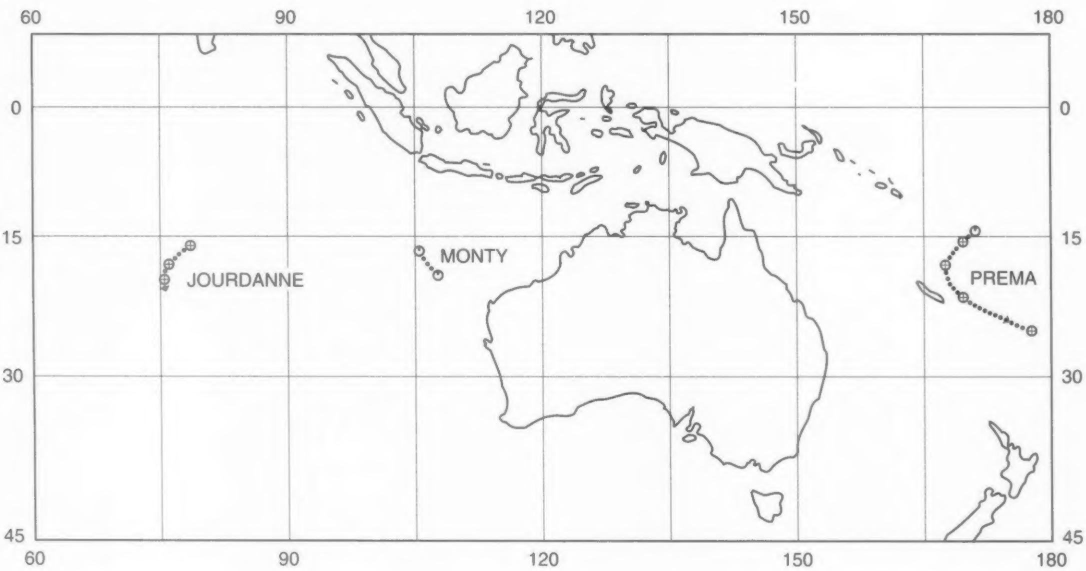
April tropical storms

This is a list of tropical storms, cyclones, typhoons and hurricanes active during April 1993. The dates are those of first detection and date of falling out of the category through dissipation or becoming extratropical. The last column gives the maximum sustained wind in the storm during this month. The maps show 0000 UTC positions: for these I must thank Julian Heming and Susan Coulter of the Data Monitoring group of the Central Forecasting Office.

No	Name	Basin	Start	End	Max. (kn)
1	Prema	AUS	27/03	01/04	120 (in March)
2	Jourdanne	SWI	03/04	09/04	120
3	Monty	AUS	10/04	12/04	50

Basin code: N — northern hemisphere; S — southern hemisphere; A — Atlantic; EP — east Pacific; WP — west Pacific; I — Indian Ocean; WI — west Indian Ocean; AUS — Australasia.

Notes: None of these storms affected land during this month.



Your Editorial Board announces that the Meteorological Office Board has decided that the publication of the *Meteorological Magazine* will cease with the issue for December 1993.

As one of the leading European establishments for research into meteorology our publications should be subject to external peer review: this is already the case for much Meteorological Office work. The publication of a new international and European quarterly journal by the Royal Meteorological Society (to be called *Meteorological Applications*) is expected to provide a suitable vehicle for the kind of articles that now appear in *Met Mag*, namely on research, practice, measurements, reviews, applications of meteorology, book reviews, etc.

The December 1993 issue of *The Meteorological Magazine* will be a bumper one of about 40 pages celebrating the Magazine's contribution to the development and dissemination of meteorological knowledge. It will contain a selection of highlights from 1866 up to around 1986.

The United Kingdom Meteorological Office (UKMO) Annual Scientific and Technical Review

This Review describes the major developments in science and technology within the UKMO over the year and is produced as part of the Meteorological Office Annual Report and becomes available in July each year. If you wish to be put on the mailing list please write to:

The News Desk,
Publications (room 709),
Meteorological Office,
London Road,
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RG12 2SZ.

Informal communications

The UKMO has instituted an in-house periodical for informal and rapid dissemination of the latest relevant science and technology news to its staff and outside collaborators. Most contributions come from UKMO staff, but offers of material from outside will be welcome — though there is no guarantee of publication.

Back numbers: Full-size reprints of Vols 1–75 (1866–1940) are available from Johnson Reprint Co. Ltd., 24–28 Oval Road, London NW1 7DX. Complete volumes of *Meteorological Magazine* commencing with volume 54 are available on microfilm from University Microfilms International, 18 Bedford Row, London WC1R 4EJ. Information on microfiche issues is available from Kraus Microfiche, Rte 100, Milwood, NY 10546, USA.

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